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Full Title	Exploring sustainable land use in forested tropical social-ecological systems: A case-study in the Wet Tropics
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Abstract

Tropical countries lie at the nexus of three pressing issues for global sustainability: agricultural production, climate change mitigation and biodiversity conservation. The forces that drive forest protection do not necessarily oppose those that drive forest clearance for development. This decoupling, enhanced by the stronger economic forces compared to conservation, is detrimental for the social-ecological sustainability of forested tropical landscapes. This paper presents an integrated, and spatially-explicit, Agent-Based Model that examines the future impacts of land-use change scenarios on the sustainability of the Wet Tropics region of tropical Queensland, Australia. In particular, the model integrates Bayesian Belief Networks, Geographical Information Systems, empirical data and expert knowledge, under a land-sharing/land-sparing analysis, to study the impact of different landscape configurations on trade-offs and synergies among biodiversity and two ecosystem services (sugarcane production and carbon sequestration). Contrary to most tropical regions, model simulations show that Business As Usual is helping to reconcile these contrasting goals in the forested landscape of the Wet Tropics. The paper analyses which combination of governance and socio-economic factors is causing these positive results. This is an outstanding achievement for a tropical region, considering that most tropical areas are characterized for having stronger economic-land clearing forces compared to conservation forces, which reduce important ecosystem services for human wellbeing and the health of ecosystems.

1. Introduction

Humans now manage the majority of land on earth, with more and more land being allocated to agriculture, especially in tropical forests, which are declining (Venter *et al*., 2016). It is, therefore, no surprise that a debate about how to reconcile the needs of people and nature has resurfaced (Fenning, 2014). This question is particularly important in tropical regions, which face three main issues for sustainability. First, future food demand is projected to increase by at least 70% by 2050 in response to growing levels of per capita consumption, shifts to animal-based diets, and increasing population (Nelleman, 2009). Improving agricultural productivity in the tropics will be critical to meet this demand (Fedoroff, 2010). Second is the need to reduce atmospheric concentrations of Greenhouse Gases (GHG) to address climate change (UNFCCC, 2009), which focuses international policy discussions on reducing emissions from tropical deforestation and degradation (e.g. UN-REDD Programme) (Angelsen, 2008). Third is biodiversity loss – the global biodiversity crisis has been well documented, with one-fifth of the world's known vertebrates being at imminent risk of extinction (Hoffman *et al*., 2014) and many more, less studied, species thought to be under similar threat (Tedesco *et al*., 2014). In tropical landscapes, land-use change (LUC), driven by the expansion and intensification of agriculture and plantations (Foley, 2005), is the main cause of biodiversity and ecosystem services (ES) loss (Harrison *et al*., 2014).

How can we achieve the greatest conservation and climate change mitigation outcomes in a landscape, given production demands for food, fibre, fuel and other ES? This trade-off is generally addressed by two broad governance strategies at the landscape level: one intensifies farming to allow the offset of areas in which nature is protected – land-sparing (LSP) – while the other integrates agricultural production and nature protection in an agro-ecological matrix – land-sharing (LSH) (Green *et al*., 2005; Hulme *et al*., 2013; Phalan *et al*., 2011). Thus, a LSP/LSH framework can be used to determine what balance of land-use intensity and conservation is needed in order to benefit both biodiversity (Gordon *et al*., 2016) and production outcomes, while considering carbon emission mitigation strategies.

This paper presents an integrated Agent-Based Model (ABM) to explore the impact of LUC forces on trade-offs and synergies among agricultural production, climate change mitigation and biodiversity conservation in the Wet Tropics Natural Resource Management (NRM) region of tropical Queensland, Australia (i.e. Wet Tropics, hereafter)[1]. In particular, the model uses the LSP/LSH framework to examine the empirical and spatially explicit impacts of three main LUC processes, i.e. land clearing, protection and restoration, on one provisioning ES (sugarcane production), one regulating ES (carbon sequestration) and biodiversity. The model, which combines Bayesian Belief Networks (BBN), Geographic Information Systems (GIS), empirical data and expert knowledge, is used to address one main research question for the Wet Tropics: which land-use and governance scenarios (Business as Usual (BAU), LSP, or LSH) help reconcile food production, climate change mitigation and biodiversity conservation, now and into the future, and why?

[1] The Wet Tropics Natural Resource Management (NRM) region is one of 56 administrative regions that the Australia Government has recognised for the purposes of NRM planning and funding (Curtis *et al.,* 2014).

2. Material and Methods

2.1. Study area and problem formulation

An empirical, and spatially explicit, ABM was constructed to explore the effect of three future LUC scenarios (BAU, LSP, and LSH) on trade-offs and synergies among two different ES (carbon sequestration, sugarcane production) and biodiversity, in the Wet Tropics of northeast Queensland (Figure 1), for the period 2016-2030. This fourteen-year outlook reflects a suitable (minimum) period of time needed to model relevant LUC in the Wet Tropics, as shown by the Land-Use Summary 1999-2015 (DSITI, 2016).

The selection of the Wet Tropics as a case-study is based on its particular socio-economic and governance context: while most tropical regions, generally located in developing countries, have weak conservation governance, corruption and relative socio-economic disadvantage – which normally enhance land clearing processes over conservation – the Wet Tropics shows a strongly institutionalized environmental conservation together with relative socio-economic advantage (Hill *et al.*, 2015a). This atypical context, i.e. high-income region with strong conservation governance, presents a research opportunity to explore sustainability in a tropical area with a different socio-economic and governance reality. Furthermore, being Australia a developed, high-income country – where some of the common socio-economic issues from tropical developing regions are relatively less important (e.g. poverty, urban growth) – enabled a focus on the relationship between LUC, ES and biodiversity, which are important topics in the conservation and development literatures (Gordon et al., 2016). Selection of the Wet Tropics as a case study, therefore, represents an information-oriented extreme/deviant sample (Flyvberg, 2006), recognized as a rigorous approach to understanding complex phenomenon, such as sustainable development options and impacts, embedded in their real-world context (Yin, 2013).

The Wet Tropics covers an area of 21,722km^2 and is the only region to include two contrasting World Heritage Areas side by side – the Wet Tropics World Heritage Area (WTWHA) and the Great Barrier Reef (GBR)[2]. The area is home to both a rich and enduring Aboriginal cultural heritage and one of the most biologically diverse areas in the world, with forests recognized as part of one of the thirty-five international global biodiversity hotspots (Williams *et al*., 2011). 50 % of current land in the Wet Tropics is protected, a considerably larger area than the main industry – sugarcane production (8%) – and the total production land – including agriculture, plantations and other intensive uses (13%) (DSITI, 2016). However, the sugarcane industry is one of the most important rural industries in Australia (AgriFutures, 2017), and its expansion would threaten the rich biodiversity of the north-east of Queensland. The current BAU context in the Wet Tropics shows an increase in protected areas by around 20% since 1999, with the area covered by sugar plantations remaining relatively stable (DSITI, 2016). Thus, a BAU scenario in our model refers to a context where protected areas increase while sugarcane production remains stable.

[2] This paper only focuses on the Wet Tropics and analyses on the GBR are beyond the current scope of our model. Although the impacts of land-use on the GB ecosystems are well-documented (Waterhouse *et al*., 2017).

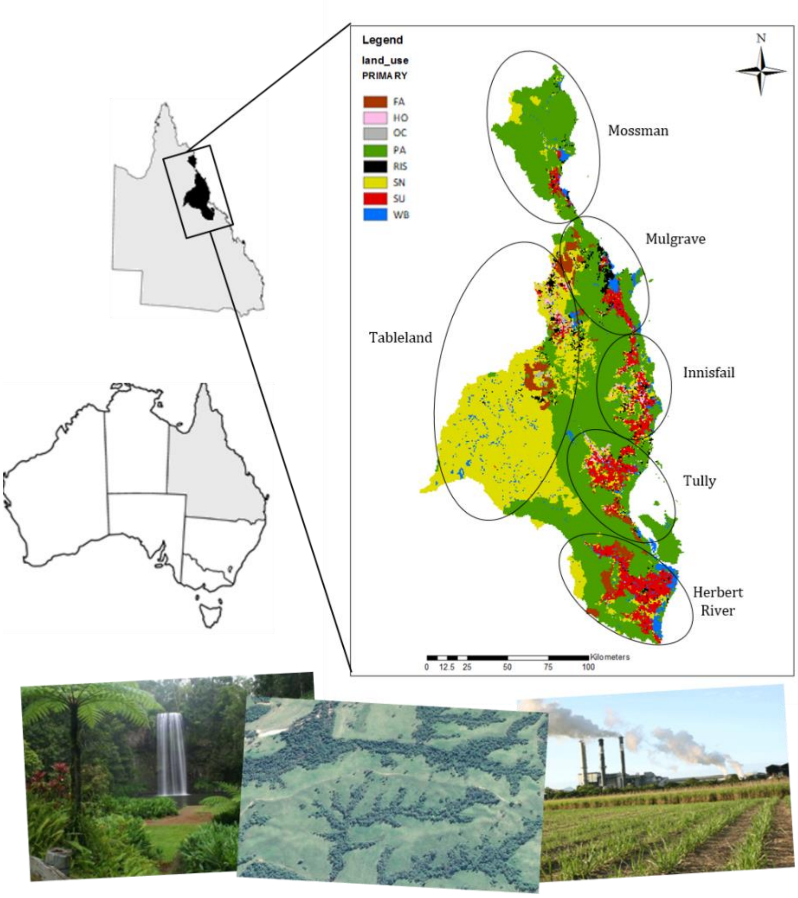


Figure 1: Geographic location of the Wet Tropics Natural Resource Management region, north-east Queensland, Australia. This digital land use map is a product of the Queensland Land Use Mapping Program (QLUMP) and was produced by the Queensland Government. The dataset comprises an ESRI vector geodatabase at a nominal scale of 1:50,000. The primary land-uses displayed are: forestry areas (FA), horticulture (HO), other crops (OC), protected areas (PA), residential and industrial areas (RIS), semi-natural areas (SN), sugarcane lands (SU) and water bodies (WB). Circled areas show the different sugarcane mill-areas present in the region. The photographs on the bottom show local examples of the three primary land-uses considered: protected (left), semi-natural (centre), and sugarcane (right) areas.

2.2. Spatially-explicit modelling of the land sharing/land sparing framework

The Wet Tropics provides a data rich case for investigation of LSP/LSH options, using a spatially-explicit model. With almost 50% of land protected, and a stable 8% of agricultural land allocated for sugarcane production, LUC processes are less frequent than in most other tropical regions of the globe (see DSITI, 2016); and, as noted above, its relative socio-economic advantage means that compounding factors such as rapid population growth and poverty are absent. The characteristic environmental conditions (with a high gradient across the landscape of rainfall and soil conditions to grow sugarcane), as well as strong conservation forces (which maintain land clearing processes at a low rate), reinforce a clear segregation of land-uses about which regularly updated data are publically available. This spatially-explicit context provides a suitable scenario to model the consequences of LSP or LSH in the Wet Tropics.

Figure 1 shows a spatial segregation of the three primary classes of land-use types in the region (i.e. protected areas (PA), sugarcane land (SU) and semi-natural areas (SN)), which creates a platform to apply this framework from a spatial perspective. The environmental and land-use characteristics of semi-natural areas align with the concept of LSH, while both sugarcane plantations and protected areas combined align with the one of LSP. More specifically, the land-use classification developed by ACLUMP[3] (2016) refers to semi-natural areas as a primary class based on production from relatively natural environments – defined as land that is used mainly for primary production with limited change to the native vegetation. Thus, semi-natural areas, which include native forests and grasslands, are subject to relatively low levels of intervention and the structure of the native vegetation generally remains intact (ACLUMP, 2016). LSH, also called ‘wildlife-friendly farming’, is known as a land-use system that combines low intensity agricultural production with protection in an agro-ecological matrix (Green *et al*., 2005; Hulme *et al*., 2013; Phalan *et al*., 2011), and therefore aligns with the semi-natural areas in our study region – as defined in ACLUMP (2016). Similarly, protected areas and sugarcane land are defined by ACLUMP (2016) as primary classes consisting of “conservation and natural environments” (including strict

[3] ACLUMP stands for Australian Collaborative Land-use and Management Program Partners. This nationally consistent document provides a land-use nomenclature and classification scheme for Australia.

nature reserves, national parks, and other conserved areas)[4] and “intensive sugarcane production from irrigated and dryland agriculture”, respectively. Thus, the combination of both protected areas and sugarcane agricultural land aligns with the concept of LSP, which is based on intensifying production to maximize agricultural yield within a fixed area, while dedicating other land to biodiversity conservation (Green *et al*., 2005; Hulme *et al*., 2013; Phalan *et al*., 2011). Table 1 shows a qualitative description of the rationale for the different scenarios modelled.

[4] Note that the ACLUMP land use “conservation and natural environments” is virtually identical in the Wet Tropics with protected areas management categories I-IV as defined by the IUCN. Some small areas of highly significant natural environments near the coastline, that are not IUCN protected areas, are categorised by ACLUMP as “wetlands” and are excluded included from our analysis. ACLUMP disaggregates “conservation and natural environments” into different protection categories, which are all integrated as “protected areas” in our model.

Scenario (2016-2030)	Description
Business As Usual (BAU): “World Heritage”	The number and extent of protected areas in the Wet Tropics keep increasing, in order to meet conservation targets for rare and endangered ecosystems. The total extent of semi-natural areas increases slightly following the trends from the period 1999-2015. Production (mainly sugarcane) remains stable over time, since other regions in Queensland (e.g. Mackay-Whitsundays) are rather focused on meeting national production demands.
Land Sparing (LSP): “World Heritage and Australia’s ‘food bowl’ region”	The region continues to meet conservation targets by increasing the number and extent of protected areas. However, this is combined with increases in the amount of land focused on agricultural (sugarcane) production, enhanced by policies of the Queensland and Australian governments. The goal is the Wet Tropic to improve its contribution to food production, part of the vision for Australia as a ‘food bowl’ for other countries.
Land Sharing (LSH): “Multifunctional landscapes”	Queensland and Australian Governments lead a transition towards more multifunctional discourses and governance framework, where wildlife-friendly farming practices are enhanced at the expense of lower sugarcane yields. Thus, the Wet Tropics follows opposite trends than in the LSP scenario, where both protected areas and sugarcane lands decrease in exchange for semi-natural areas, providing for multiple community values and lifestyles.

Table 1: Narratives of the scenarios modelled for the period 2016-2030.

In short, our model explores LUC dynamics with regard to semi-natural areas (LSH) and the nexus of protected areas–sugarcane land (LSP). The LUC scenarios explored include LSH (where semi-natural areas increase/decrease), LSP (where protected and sugarcane areas increase/decrease) and BAU (where protected areas increase at the same rate as during the period 1999-2015) (see DSITI, 2016). Our model explores the impact, over time, of these LUC processes on sugarcane production, carbon sequestration and biodiversity conservation. In this regard, although LSP versus LSH studies are usually focused on minimizing trade-offs between biodiversity and a production goal (sugarcane in this case), our research also integrates the study of one other ES (i.e. carbon sequestration) due to the importance, from an environmental perspective, of carbon emissions from deforestation in tropical regions. Furthermore, the spatially-explicit nature of the model aims to contribute to the lack of spatially-explicit LSP/LSH studies (Fischer *et al*., 2014; Law *et al*., 2015).

2.3. Modelling framework

ABMs are argued to be helpful for studying complex dynamics in social-ecological systems (SES), as well as gaining insights that support the sustainable management of natural resources (An *et al*., 2014; Filatova *et al*., 2013; Gonzalez-Redin *et al*., 2018; Schulze *et al*., 2017). The ABM presented in this paper can be considered to be an Agent-Based Land-Use Model (ABLUM) (see Matthews *et al*., 2007; Polhill *et al*., 2011), which combines BBN, GIS, empirical data and expert knowledge. This integrated modelling approach aims to contribute to one main demand within both the ABM and ABLUM communities (O'Sullivan *et al*., 2016): to build hybrid ABMs that integrate different techniques and, thus, capture the advantages of different modelling approaches.

Here, BBNs – constructed using GeNIe builder tool (GeNIe and SMILE, 1998) – and GIS layers – using ArcGIS and QGIS –, as well as empirical data and expert opinion, are integrated into an ABM – constructed using NetLogo (Wilensky, 1999). Figure 2 shows the modelling framework of our model; note that the ‘integrated’ characteristic does not refer to the actual integration of an ABM software into a GISystem or BBN software – or the other way around – but to the use of spatial data (i.e. GIS layers) and BBNs in a NetLogo model.

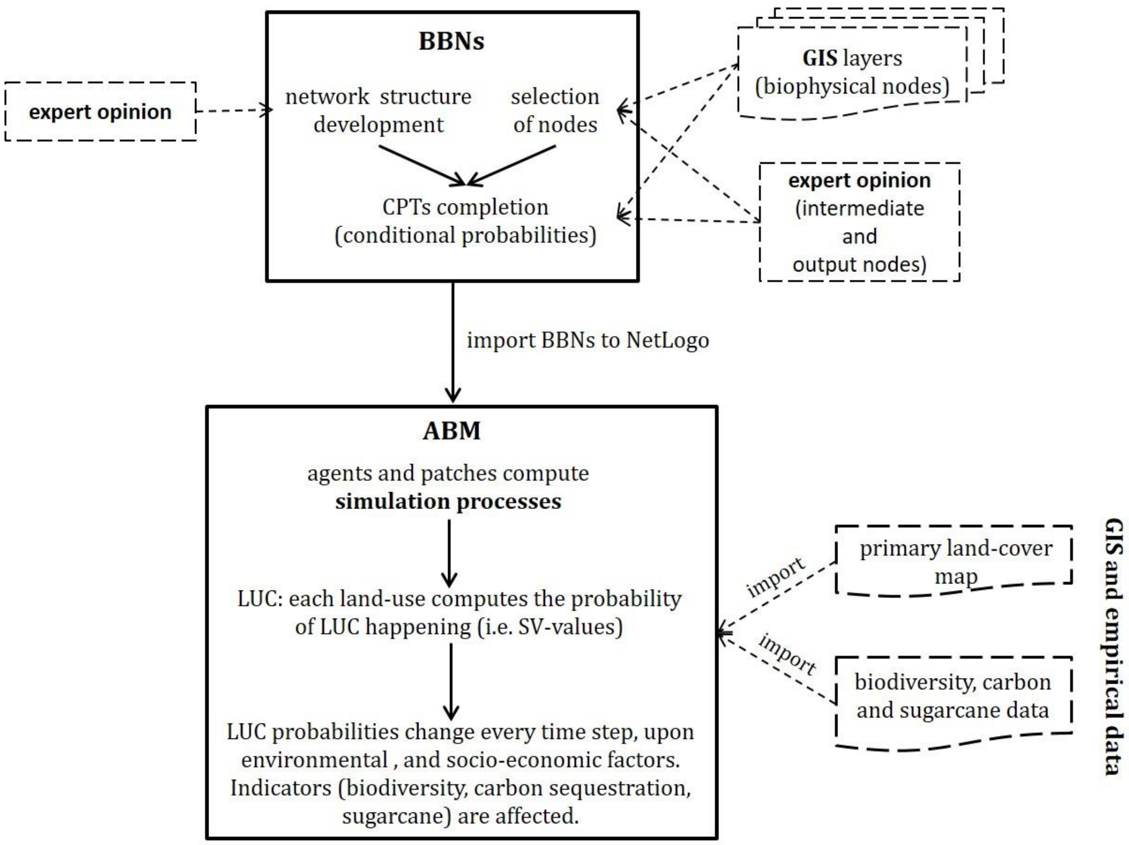


Figure 2: Modelling framework; where the different modelling techniques and data sources – i.e. ABM, BBN, GIS, empirical data and expert knowledge – are combined together to build the integrated model presented.

The model building process started by importing the primary land-cover map for the Wet Tropics (DAF, 2015) as a vector file into NetLogo. This process provided an initial distribution of land-uses for the case-study area, where the land-use map shown in

Figure 1 was imported into NetLogo (i.e. the map in Figure 3. As a result, each cell in our NetLogo model covers an area of 123.64ha of the case-study area (see ‘Importing GIS layers into NetLogo’, SI document, for details). Out of the ten land-use types present in the Wet Tropics (see Figure 3), only three are considered for our research analysis. These include: rainforest (protected areas), native pasture & production forestry (semi-natural areas), and sugarcane land (developed areas). These three land-use types cover 97 % of the total land in the Wet Tropics. Furthermore, the focus on these land-uses follows the LSP versus LSH rationale explained at the beginning of the Material and Methods section, as well as the conceptual model developed by Hill et al. (2015b). The LUC for the remaining seven land-uses (hereafter called ‘other land-uses’, see UML diagram in Figure 4) are not analysed in the Results (3) section, although their LUC processes are still computed for the sake of realism.

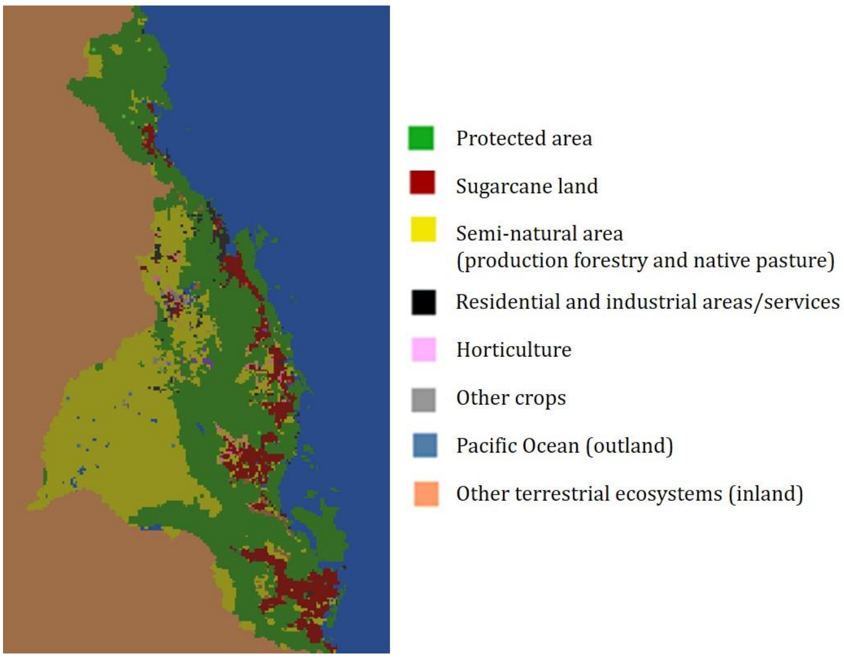


Figure 3: Initial (2015) primary land-use distribution for the Wet Tropics, obtained by integrating a primary land-use map (DAF, 2015) into NetLogo. Note that the case-study area is located between the Pacific Ocean (to the right, in blue) and other terrestrial ecosystems (to the left, in light orange), which are not considered for this research. The legend from this figure is also used for Figure 6 below.

Sections 2.4 and 2.5 below explain, in detail, the interactions among entities (agents) in the ABM and the simulation processes of the model. Simultaneously, BBNs in our model are used to compute LUC. Although the use of BBNs for modelling LUC is not new (Celio *et al*., 2014; Lynam *et al*., 2002), examples of the incorporation of BBNs into spatial ABMs are scarce (Kocabas *et al*., 2013; Sun and Müller, 2012). Moreover, BBNs can help in addressing uncertainties (Gonzalez-Redin, *et al*., 2016; Perez-Minana, 2016; Smith, *et al*., 2017), such as those regarding LUC decision-making.

Our BBN building process followed a logical framework adapted from the Australian Department of the Environment, Heritage and the Arts (DEWHA, 2010). In particular, our BBNs provide information to ABM agents (i.e. agents responsible for driving LUC) on what type of LUC, and where exactly, needs to be computed in each time step. Thus, the BBNs help agents answering questions such as: *is a land-use with high conservation potential and low production potential suitable to be protected, under a BAU scenario?; Is a land-use with moderate carbon sequestration potential and low conservation potential suitable to be converted into sugarcane plantations, under a LSP scenario?* The BBN probabilities were established based on GIS and empirical data, as well as expert opinion. The BBNs were then imported to NetLogo through reporters that compute tables including the BBN probabilities. Table S5 (SI document) shows the different GIS data used, while the section '2.6 Bayesian Belief Networks and Expert knowledge' below describes the integration of expert opinion in the BBNs and provides more details on the use and integration of BBNs in our ABM.

At the same time, each land-use computes its own biodiversity, carbon sequestration and sugarcane values – which are analysed in the Results section. These indicators, which are affected by the above-noted LUC processes, are initially imported to the model based on both available published empirical data – e.g. sugarcane yield, sugar price, carbon price (see Table S4, SI document) – and GIS layers (see Table S5, SI document).

Finally, a sensitivity analysis was performed based on an OFAT (One-factor-at-a-time) process (ten Broeke *et al*., 2016). See SI document for details.

2.4. Entities, state variables and scales

In our model, LUC processes are computed by agents (called *PG-agents*) – which represent the power of governance forces driving LUC. *PG-agents* are classified into three types, based on the previously described LSP/LSH framework: PG_d (governance forces driving development of land for sugarcane production, i.e. LSP), PG_p (governance forces driving the creation of new protected areas, i.e. LSP), and PG_{mr} (governance forces driving restoration and maintenance of semi-natural areas, i.e. LSH). Land-uses (called *A*) are also classified into three types: A_p (protected areas), A_a (semi-natural areas), and A_d (sugarcane areas). In addition, semi-natural areas are divided into A_{ag} (native pasture) and A_{ap} (production forestry); this subdivision is performed based on the different LUC processes characteristic of A_{ag} and A_{ap}, as well as their different ES and biodiversity values. Figure S1 in the SI document shows a Unified Modelling Language (UML) class diagram of the model entities and variables, as well as their links; Tables S1, S2 and S3 show a detailed description of the entities and state variables modelled, while Tables S4 and S5 show the initial values for the parameters modelled from both empirical and GIS data, respectively.

The spatial-scale of the model is regional. Regional scales are considered more operational in policy-making compared to larger or smaller spatial levels (Wi, 2013). More specifically, the scale of our model is directly relevant to the management of the

Wet Tropics, considering that the region is managed at the level of the World Heritage Area through the Wet Tropics Management Authority (WTMA, 2018). Likewise, *PG-agents* represent forces driving LSH and LSP processes at the regional level. For instance, PG_d*-agents*, although not modelled as actual farmers owning land parcels (*A*), move around the landscape representing those policies, incentives and governance forces driving agricultural expansion by farmers – which is the main land clearing process occurring at the landscape/regional level in the Wet Tropics (Hill et al., 2015a). The same is the case for both PG_p*-agents* and PG_{mr}*-agents*, which represent protection and restoration strategies implemented at the World Heritage Area level (i.e. regional scale) by the Wet Tropics Management Authority (Hill et al., 2015a). Hence, *PG-agents* are not simulated as agents owning land parcels, but rather as forces, resulting from governance arrangements, that move around the landscape and drive LUC, in patterns based on empirical data and expert knowledge (explained below).

The time-scale of the model was based on expert knowledge (see ‘Expert knowledge’ below). To decide how many time steps corresponds to one year in the model, experts used historic LUC data from the Department of Science, Information Technology and Innovation (DSITI, 2016) of Queensland. First, the yearly average change (in percent values and hectares) regarding the three main LUC modelled was calculated for the period 1999-2015. Second, preliminary model outputs from the BAU scenario were analysed in order to estimate how many model time steps were needed to simulate the above-noted yearly LUC values. As a result, LUC processes occurring in 20 time steps in the model correspond to one year in the real world; thus, after 300 time steps the model is considered to have simulated 15 years, with 2016 and 2030 as initial and final years, respectively.

2.5. Simulation process and overview

Figure 4 shows a UML activity diagram representing the main dynamics of the system, and the flow from one process to the next one. The following is a list of the model processes taking place every time step, which are described in detail below (see 'Submodels' in SI document for a detailed description of model functions and algorithms): (i) scenario selection; (ii) 'other land-uses'[5] compute LUC; (iii) land-uses(patches/cells) compute LUC-suitability (*SV*) values from BBNs; (iv) PG-agents compute movement based on *SV-values*; (v) PG-agents compute PR-value and patches compute LUC; (vi) land-uses (patches/cells) compute indicators.

[5] These refer to all land-uses (except sugarcane, protected and semi-natural), which are modelled but not analysed in the Results.

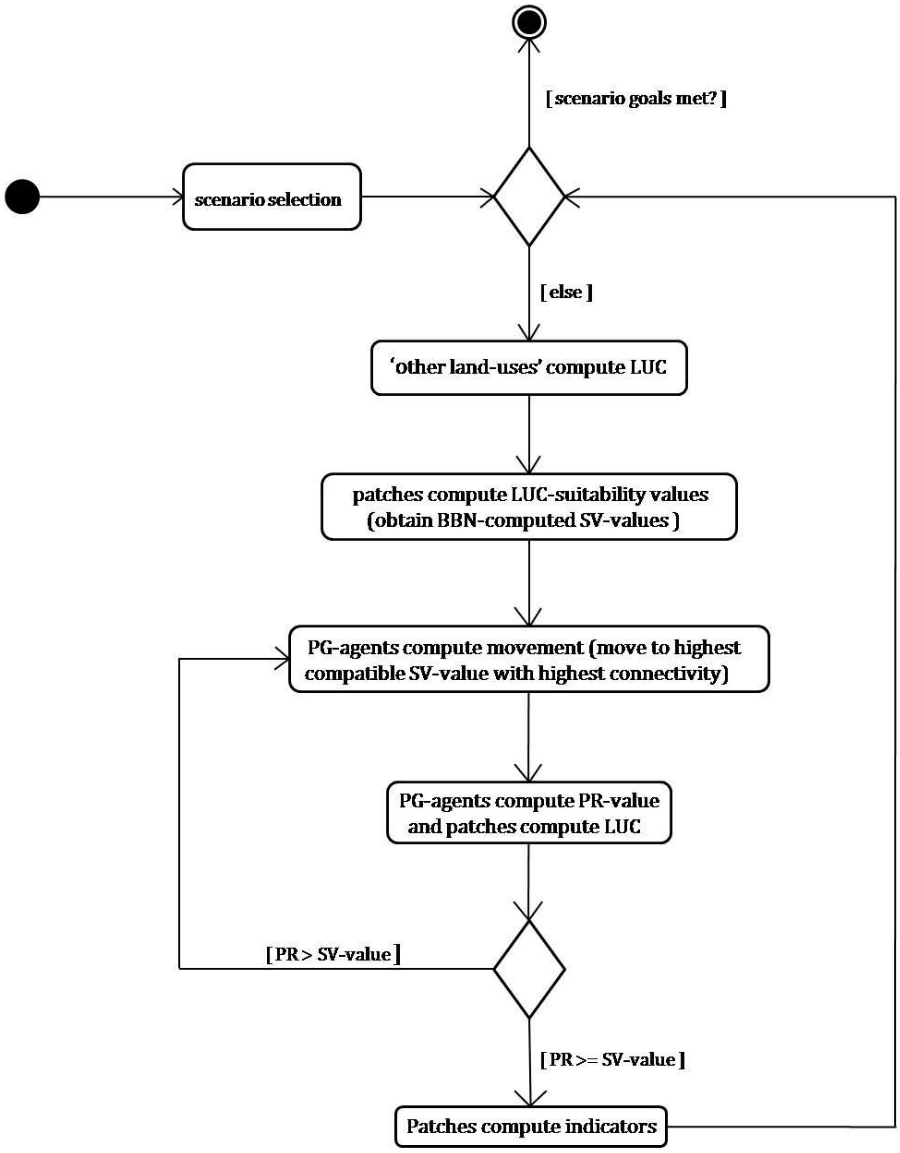


Figure 4: UML Activity Diagram. Structure diagram showing the step by step process computed by *PG-agents* and land-uses (patches/cells) in the model.

The environment consists of a grid of land-uses, where *PG-agents* move around the landscape representing forces driving LUC. Computation of LUC follows the following rationale: for each land-use cell, a total of three LUC suitability values (i.e. *SV-values*) are computed per time step, one for each type of LUC (protection, restoration, and land clearing for sugarcane). Thus, for each land-use one value for SV_p (suitability of the land-use, if unprotected, to become a protected area, or to remain as protected if already protected), another for SV_{mr} (suitability of the land-use to be converted to semi-natural land, or to remain as semi-natural if already semi-natural), and SV_d (suitability of the land-use to be converted to sugarcane, or to remain as sugarcane land if already a crop) is computed. Thus, *SV-values* state the probability of each land-use to be converted to another land-use, or to remain the same. *SV-values* are obtained from GIS and BBN (explained below) and vary from one scenario to another.

Every time step, each *PG-agent* selects the land-use with the highest compatible (to this *PG-agent*) *SV-value*. Thus, *PG_p-agents* only search for *SV_p-values*; *PG_{mr}-agents* only for *SV_{mr}-values*; and *PG_d-agents* only for *SV_d-values*. Moreover, each type of *PG-agent* selects the land-use with the largest number of neighbouring land-uses corresponding to that *PG-agent* type (this is computed to enhance patch/cell connectivity). For instance, *PG_p-agents* seek land-uses with more A_p land-uses around, *PG_d-agents* for A_d, and PG_{mr}-agents for A_{mr}. If there are no land-uses of the same type in neighbouring land-uses, the searching 'radius' is increased until land-uses of the same type are found.

Based on these rules, every time step each *PG-agent* will select one single final land-use, called *target-patch*. *PG-agents* then move to their corresponding target-patch and compute one random-float number between 0 and 1, called *PR-value*: if the value lies between 0 and the *SV*-value in the target-patch, LUC in this land-use is computed. Hence, the higher the *SV-value* in one land-use, the higher its probability to compute LUC. If the value does not lie between 0 and the *SV-value,* the land-use remains as it is.

This cycle is computed every time step for each *PG-agent*, thus driving model outcomes. Regardless of whether LUC takes place or not, each land-use computes different sugarcane production, carbon sequestration and biodiversity algorithms every time step. Note that there are no associated costs to agents' movement, since *PG_d-agents*, *PG_p-agents* and *PG_{mr}-agents* represent forces – reflecting governance arrangements – that drive LUC, and not specific schemes or policies that could be specifically accounted.

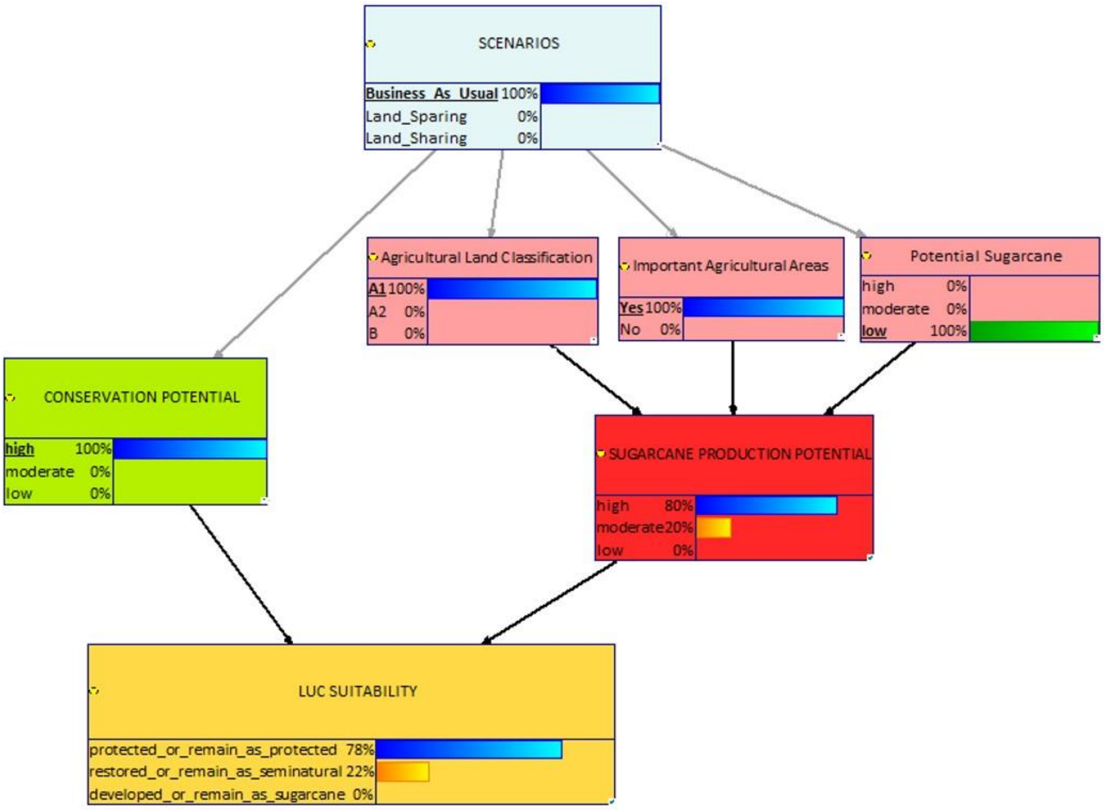
A full Overview, Design concepts, and Details (ODD) protocol, describing the model in detail, is available in the Supporting Information (SI) document.

2.6. Bayesian Belief Networks and expert knowledge

A BBN is a graphical representation of a set of variables (nodes) and their causal relationships (links), forming a directed acyclic graph (Charniak, 1991). Nodes represent system variables, such as biodiversity or sugarcane yield, while links represent causal probabilistic relationships between two nodes. Within a BBN, each node has a defined set of states/categories, along with a Conditional Probability Table (CPT), which defines, for each category, the probability of it occurring given all possible category combinations from the (parent) nodes.

In our model, BBNs are integrated in our ABM and updated every time step based on *PG-agents*' LUC decision-making, where one BBN is created for each analysed land-use type (i.e. A_p, A_a, A_d). Nine total BBNs are computed, i.e. one BBN per type of *PG-agent* (3) under each scenario (3), where each BBN has the same structure and nodes as the one shown in Figure 5. The probabilities in each CPT change every time step, where initial values are set based on a product between expert opinion and GIS data. While the CPT categories from the input nodes (e.g. 'Agricultural Land Classification' in Figure 5) reproduce the attributes from the GIS layers – thus no expert-based interpretation is needed for their completion – the CPTs from intermediate (i.e. 'Sugarcane Production Potential') and output (i.e. 'LUC Suitability') nodes are completed using expert opinion. Finally, the 'LUC Suitability' output node has three different categories, one for each type of LUC process (protection, restoration and production/development). With a value between 0-1, each category from this output node estimates the probability for each LUC type to take place in each land-use every time step (i.e. *SV-values*).

The probabilities of those CPTs from intermediate and output BBN nodes (Figure 5) were computed using expert opinion. In order to gather expert-based qualitative data, the 'focus groups' method was used (Kitzinger, 1994; Morgan, 1998; Gill *et al*., 2008). Furthermore, target values each scenario and the model's time-scale were established through expert knowledge and discussed during the focus group meetings. See 'Integrating expert knowledge in the model' section in the SI document for more details.



Conservation Potential	high			moderate			low		
Sugarcane Production Potential	high	moderate	low	high	moderate	low	high	moderate	low
protected_or_remain_as_protected	0.7	0.85	1	0.55	0.6	0.65	0.4	0.45	0.5
restored_or_remain_as_seminatural	0.3	0.15	0	0.45	0.4	0.35	0.6	0.55	0.5
developed_or_remain_as_sugarcane	0	0	0	0	0	0	0	0	0

Figure 5: Bayesian Belief Network (BBN). Example of a BBN developed using GeNIe®, with a Conditional Probability Table (CPT) on the bottom. Both light red and green boxes represent biophysical spatially explicit (i.e. GIS) nodes (i.e. input nodes), while dark red (i.e. intermediate) and yellow (i.e. output) nodes are completed using expert knowledge. Coloured bars represent the conditional probabilities for each CPT category. This particular BBN example is computed by semi-natural land-uses under the BAU scenario. In this particular case, the probability for one semi-natural land-use to be protected, having 100 % of 'Conservation Potential' and 80 % of 'Sugarcane Production Potential', is 78 %, being the probability to remain as semi-natural 22 %, and to become developed 0 %. Due to 78 being higher than 22, the prior would computed as *SV-value* for this specific land-use.

3. Results

Results regarding the indicators selected were obtained for each of the three scenarios (BAU, LSP, LSH), and grouped into their spatial and empirical impacts. A qualitative analysis was performed because of our main interest in exploring the overall differences, in trends, among the indicators and scenarios tested.

3.1. Estimated spatial impacts

Figure 6 shows the spatial explicit outputs obtained with NetLogo – note that the legend from Figure 3 is used to describe Figure 6. Three output maps were obtained for each scenario, one for each time step (year) – 2020, 2025 and 2030 – resulting in nine maps in total. The following sections (3.1.1-3.1.3) describe the spatial results obtained for each of the three scenarios (BAU, LSP, LSH).

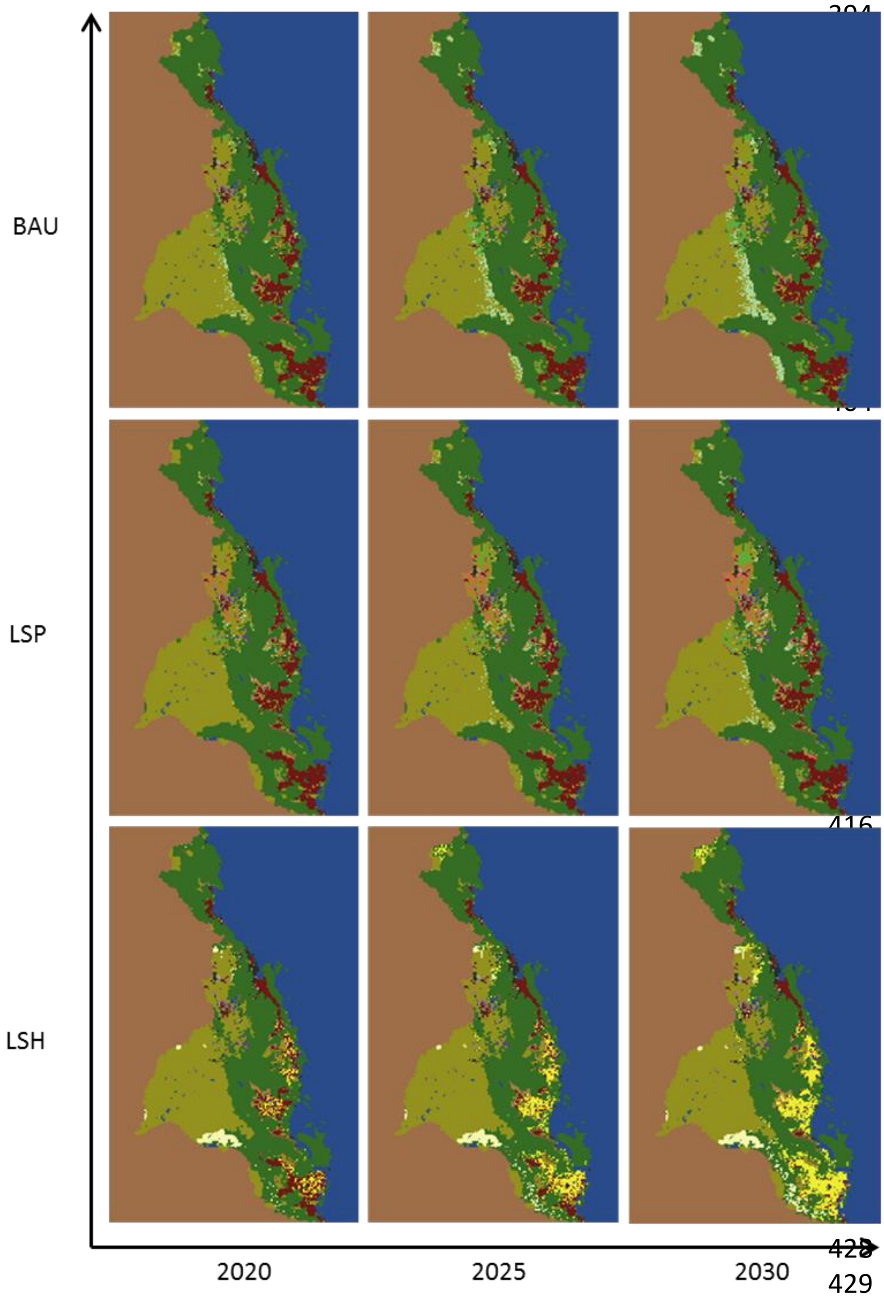


Figure 6: Spatial scenario outputs. Land-use variations are shown for each scenario (BAU = Business As Usual; LSP = Land-Sparing; LSH = Land-Sharing) regarding the years 2020, 2025 and 2030. Note that the legend from figure 3 has to be used for this figure.

3.1.1. Business As usual (BAU)

The top row of Figure 6 shows the spatial distribution of land-uses for the BAU scenario. In this scenario, protected areas increase by 10% in order to meet the conservation targets of the World Heritage listing, while production (mainly sugarcane) remains stable over time. The most spatial noteworthy trend is based on those semi-natural areas (i.e. native pasture and production forestry) with low sugarcane production potential and high conservation potential values being converted into protected areas – mainly located to the west of currently protected rainforests. Other potential sites for new protected areas are located in the north-west (Mossman) and south-west (Herbert River) areas (see Figure 1 for the specific location of these areas). As estimated below, this scenario has positive impacts on biodiversity and carbon sequestration, but negative impacts on sugarcane production.

3.1.2. Land Sparing (LSP)

The Wet Tropics continues to meet conservation targets by increasing protected areas by 5%, combined with increases in sugarcane production by 22%. Figure 6, in the middle row, shows the spatial distribution of new protected areas and new sugarcane lands converted from semi-natural areas. Semi-natural areas with high conservation potential, and low sugarcane production potential values, have a higher probability of being protected; while those with high production potential and low conservation values have a higher probability of being developed (for sugarcane production). New protected areas follow a similar spatial distribution pattern as in BAU scenario; however, their extent is lower due to new sugarcane land occupying semi-natural areas that could have become protected otherwise. New sugarcane areas are mainly located to the east of the Tablelands, with smaller areas in Innisfail, Tully and Herbert River. As estimated below, this scenario has positive impacts on sugarcane production and negative, or relatively stable, impacts on biodiversity and carbon sequestration.

3.1.3. Land Sharing (LSH)

The Queensland and Australian Governments lead a transition towards a more multifunctional discourse (i.e. LSH), where wildlife-friendly farming practices (i.e. semi-natural areas) are enhanced (30%) at the expense of sugarcane yields and protected areas. In Figure 6, the maps in the bottom row show new semi-natural areas (i.e. native pasture and production forestry) converted from previously protected and sugarcane lands. While new native pasture areas are mainly converted from previously protected rainforests with low conservation value (Tablelands), new production forestry areas are converted from both previously protected areas and sugarcane lands with low conservation and production potential values, respectively, located to the centre-east of the study area, i.e. Innisfail, Tully and Herbert River. This specific distribution, i.e. low vegetated native pasture to the west and highly vegetated forestry areas going from the center to the east, is due to rainfall values. Rainfall is an important factor in the tropics, limiting the extent to which highly vegetated and forested areas grow with rainfall values lower than 1,431mm. In the Wet Tropics, those areas with rainfall values above 1431mm are located from the center to the east, i.e. all areas but the Tableland (see Figure 1). Thus, areas located to the west have a higher probability to be converted into production forestry, while areas to the east (i.e. Tableland) are more likely to show native pasture. As estimated below, the LSH scenario has relatively stable, or positive, impacts on biodiversity and carbon sequestration, yet negative impacts on sugarcane production.

3.2. Estimated impacts

Figure 7 shows the empirical graphical results from the indicators selected.

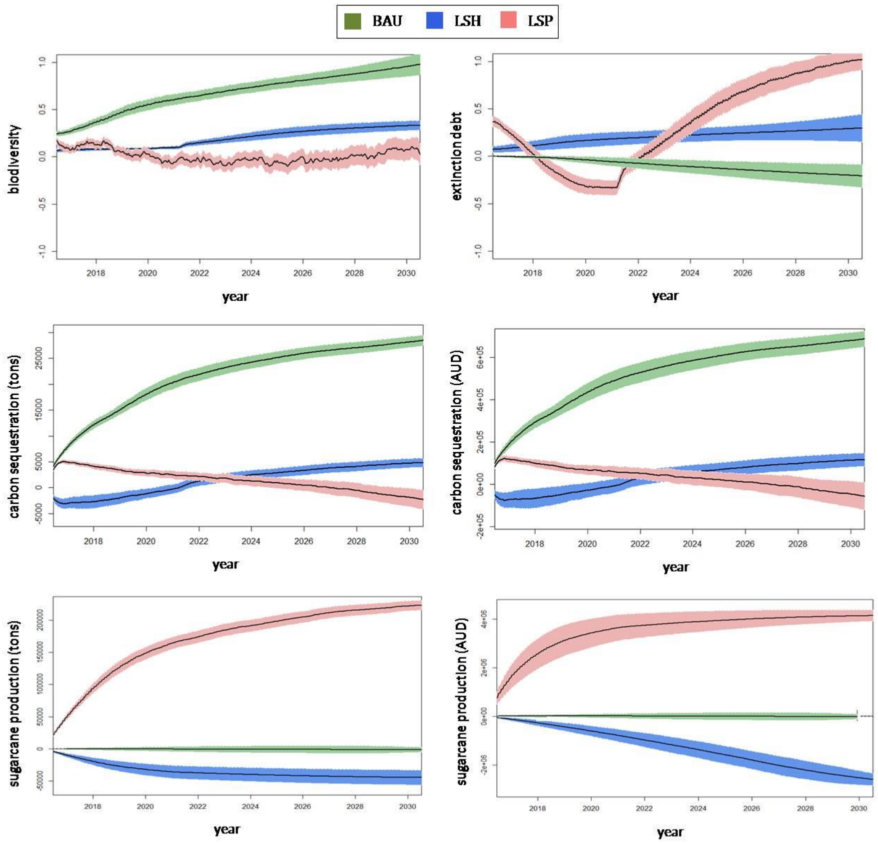


Figure 7: Graphical scenario outputs. Results are shown as the temporal variation (in net gains & losses) of different socio-economic and environmental indicators for each scenario: BAU = green; LSP = red; LSH = blue (see legend). Both sugarcane production and carbon sequestration are shown in tons and Australian Dollars (AUD). Colour bands represent the standard error bands regarding all the runs computed for each indicator under every scenario. The black coloured lines show the mean values.

Biodiversity and extinction debt indicators show the variation of current biodiversity values and the future extinction of species due to events in the past, respectively; where the latter occurs because of time delays between impacts on species and the species' ultimate disappearance (Jackson and Sax, 2010). In short, biodiversity shows the 'gross' biodiversity, whereas extinction debt shows the 'net' (future) biodiversity. The BAU scenario (Figure 7) shows positive trends for biodiversity and slightly decreasing for extinction debt, while LSH shows slightly positive trends for both indicators, and LSP shows a steady stable trend for biodiversity and a decrease, followed by an exponential increase, for extinction debt. Both biodiversity and extinction debt vary based on the proportion of habitat restored and destroyed, as well as habitat connectivity, i.e. the higher the connectivity and habitats restored, the higher biodiversity and lower extinction debt values. Thus, while BAU may be a sustainable scenario for biodiversity in the short-term (see biodiversity, BAU), this scenario could end up diminishing the biodiversity in the long-term (see extinction debt, BAU). Similarly, yet to a higher extent, the exponentially increasing extinction debt values obtained for LSP after 2021 could also mean that biodiversity would end up dropping under LSP practices in the long-term (see extinction debt, LSP), regardless of the current relatively positive biodiversity results (see biodiversity, LSP). The Discussion (4) section analyses the importance of extinction debt and net biodiversity values in the Wet Tropics.

Regarding sugarcane production, BAU shows steady state sugarcane values (both in tons and monetary value), whereas LSH shows decreasing values and LSP increasing. Sugarcane values increase with more land cleared for agriculture, such as (partially) in LSP, while production decreases with area protection (BAU) and restoration processes (LSH). The reason why sugarcane production does not decrease under BAU – where more and more areas are protected – is because such protection occurs in current semi-natural areas instead of sugarcane land. Carbon sequestration values, likewise sugarcane production, change over time based on LUC, which affects vegetation cover and growth. Here, BAU shows an exponential increase in the amount of carbon sequestered and LSH shows a relatively linear increase. LSP, in contrast, is the only scenario showing negative values for carbon sequestration (both in tons and monetary value).

Figure 8 shows the power and influence of protection and development forces on biodiversity, at the landscape level. In particular, it shows the impact on biodiversity of two sets of cases with different initial amount of protection forces driving land protection (*PG_p-agents)* and development forces driving land clearing for sugarcane production (*PG_d-agents)*. The heatmap on top of Figure 8 shows biodiversity results with one single initial *PG_p-agent* and different initial number of *PG_d-agents*, while the bottom heatmap shows results for one single initial *PG_d-agent* and different initial number of *PG_p-agents*. The higher variability of biodiversity in the top heatmap compared to the bottom heatmap shows that, as expected, biodiversity in the Wet Tropics increases considerably with stronger protection forces (i.e. higher number of *PG_p-agents*). In contrast, development forces (*PG_d-agents*) have a limited influence on biodiversity (bottom heatmap) even in those scenarios with strong development forces driving land clearing for agriculture (i.e. higher number of *PG_d-agents*). These results provide a baseline for governance discussion addressed in the Discussion (4) section.

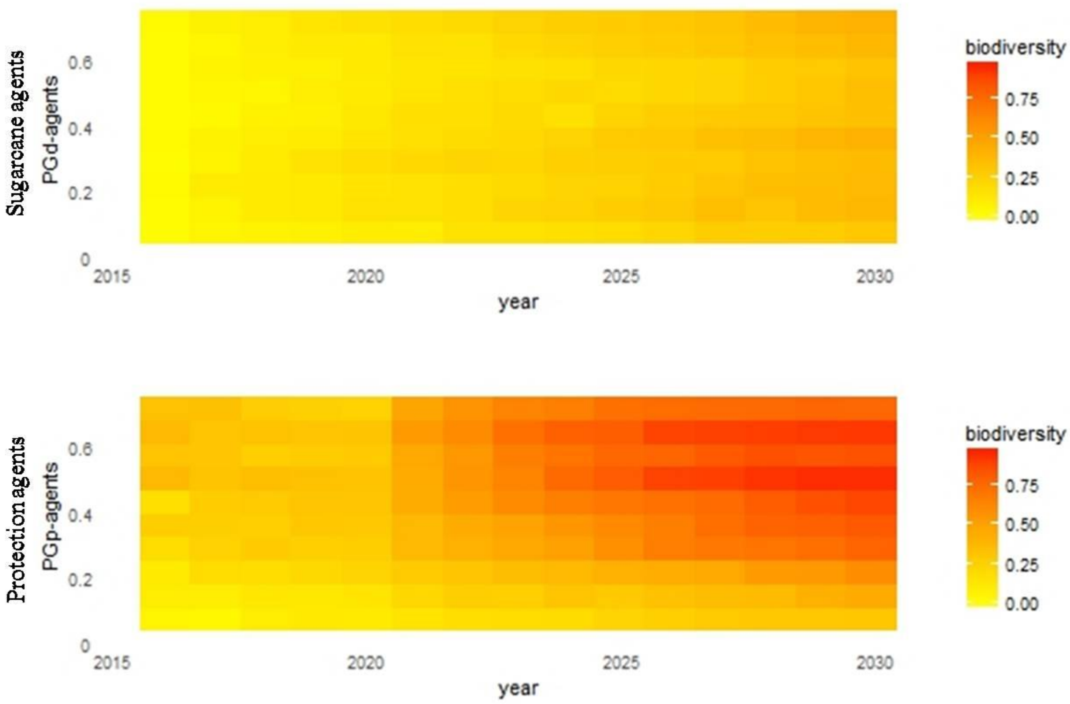


Figure 8: Impact of governance and political policy forces on biodiversity. *PG_p-agents* and *$PG_{\cancel{p}d}$-agents* refer to conservation and development forces, respectively. The heatmap on top shows biodiversity variation over time considering the minimum number of initial *PG_d-agents* (i.e. five) for different initial *PG_p-agents* (i.e. values on Y-axis). The bottom heatmap shows biodiversity variation over time considering the minimum number of initial *PG_p-agents* (i.e. five) for different initial *PG_d-agents*. Only results for the LSP scenario are shown due to this scenario including development and protection forces competing for land.

4. Discussion

What socio-economic, governance and environmental factors are helping to reconcile food production, climate change mitigation and biodiversity conservation in the Wet Tropics?

Under the framework and modelling approach considered, results show that the BAU scenario in the forested landscape of the Wet Tropics is helping to provide food, conserve biodiversity and sequester atmospheric carbon. These results are of more importance, considering that this tropical area – as with other tropical regions – is managed under global and national market economies that generally favour land clearing for agriculture over conservation (Balls, 2018). Furthermore, translating the results from Figure 8 into a governance context, the current strength of the power of governance in the Wet Tropics focused on protecting rainforests, maintaining high biodiversity and limiting land for development, is relatively high. Similarly, the strength of the power of governance driving land clearing for sugarcane production in the Wet Tropics is not sufficiently strong to decrease biodiversity, even in those scenarios where development forces are considerably stronger than protection forces. Therefore, these results, together with the biodiversity outcomes obtained under BAU scenario (Figure 7), show that the Wet Tropics would not need excessive additional conservation governance power in order to maintain the current increasing biodiversity and carbon sequestration trends.

As shown by our model, the positive biodiversity and carbon sequestration results under BAU, with stable sugarcane production values, have their origin in the stronger conservation forces compared to economic, land clearing forces in the Wet Tropics. Although not empirically addressed in our model (yet integrated in the conceptual nature of *PG_p-agents*), we argue that the combination of both strong bottom-up and top-down conservation forces has been the main driver of such outcomes over the past decades. Bottom-up forces started to originate in the 1970s, through the growing public knowledge and awareness of the (environmental, social and economic) significance of wilderness areas in this region (Burg, 2017). Thus, the lack of substantial environmental movement that had dominated the North Queensland society since settlement in the 1860s started to change. Conservation groups, local citizens, and prominent national and international scientists initiated a drive, based on lobbying, direct action, mass mobilisation and political endorsements, against the economic forces driving land clearing. This bottom-up movement was able to change public and government attitudes towards preserving the natural environment, thus shifting conservation strategies from a regional- to a national- and at times a global-arena (Burg, 2017). Eventually, the Australian Government became involved in the decision-making process, and the campaign culminated in the listing of the Wet Tropics rainforests on the World Heritage Register in December 1988, as well as the formation of the Wet Tropics Management Authority. This lead to the beginning of a wide, strong and multilayer policy network for the protection of rainforest biodiversity in the region (i.e. top-down conservation force). Currently, this multilayer policy network enables flexible, targeted responses to multiple and overlapping threats to biodiversity (Hill *et al*., 2010; Hill *et al*, 2015ab). The result: currently almost 50% of the Wet Tropics is protected (DSITI, 2016), mainly rainforest, helping to protect biodiversity and enhance the supply of multiple ES, such as global climate regulation, air quality regulation, and cyclone protection (Alamgir *et al*., 2016).

In addition to the combination of bottom-up and top-down forces, we argue that conservation in the Wet Tropics has also been strengthened due to different factors:

(1) *social-political* – timber harvesting from the tropical rainforests of north Queensland ceased following their inscription on the World Heritage List in 1988 (Vanclay, 1993). This helped re-electing a national government that took advantage of the above-noted bottom-up advocacy (i.e. environmental awareness) to make removing logging from the Wet Tropics a vote-winner nationally (Redfield, 1996). This decision was controversial in the sense that the Queensland Government, which was responsible for managing logging in state owned rainforests, argued that logging in this region was highly efficient, selective and intermittent compared to tropical forestry elsewhere – with low scale disturbances, similar to cyclone damages, to which the ecosystem is historically adapted (Nicholson *et al*., 1990). Regardless of whether imposition of rainforest conservation by the Australian Government was positive or negative, support for conservation by politicians, even if it was for their own political benefit, was an important factor enhancing environmental sustainability in the Wet Tropics. (2) *Legal* – under the Australian Constitution, the national government can over-ride the State Governments over matters tied to international treaties, such as the World Heritage Convention. Although the management of the region itself is a matter for the Queensland Government, the Australian Government can stop environmentally unsustainable activities, such as the logging of the Wet Tropics forests.

(3) *Environmental-scientific* – the region is the 2nd most irreplaceable World Heritage area globally in terms of its biota, including remnants of Gondwana that are not found elsewhere (Queensland Government, 2018). Because the Wet Tropics is a World Heritage Site (in contrast to most tropical areas located in developing countries) and a conservation hotspot, it is easier to justify and receive support with regard to conservation; (4) *Economic* – the tropical forests are around twenty times less productive of timber than temperate forests, where the latter provides the vast majority

of the world’s industrial wood (i.e. 75%) (FAO, 2004; Sedjo and Simpson, 1999). Furthermore, with the World Heritage protection in 1988 came the banning of logging within the now protected forests (Vanclay, 1994), where today only reduced forest clearing and selective harvesting continues on private land. Thus, timber production from forests in the Wet Tropics is a relatively un-competitive economic use (Valentine and Hill, 2008). Besides this, the eco-tourism industry in the Wet Tropics – which is making a large contribution to the national economy (WTTC, 2017) – is currently helping to diminish the influence and need of agriculture and timber industries as economic drivers of the Wet Tropics. Besides this, Australia is a rich, developed country, which translates into more funding allocated for conservation programmes – compared to developing countries, which are more focused on solving poverty and social issues (Ceddia *et al*., 2014; Hill *et al*., 2013). (5) *Governance* – public governance in Australia, compared to other countries in Southeast Asia, is currently doing better with regard to different indicators, such as corruption and poor governance (Sodhi *et al*., 2010). Countries with governments that have low values for conventional indicators (e.g. corruption control, quality public services) are more likely to experience the spatial expansion of agriculture, while those governments with high quality environmental governance (e.g. reduce environmental stress, increase ecosystem vitality) generally show agricultural spatial contraction (Ceddia *et al*., 2014). Furthermore, public governance in Australia is more responsive to public opinion, which currently supports, and requires, the sustainable use of natural capital in the Wet Tropics. (6) *Geographical* – Australia has no spatial conflicts with neighbouring countries (in terms of landscape management and protected area creation). Thus, the Queensland Government can manage the Wet Tropics without having to deal with potential cross-national or international conflicts.

These factors have created a context in the Wet Tropics where conservation is prioritized over land clearing for agriculture. Yet, regardless of the positive short- and medium-term results obtained for biodiversity and conservation (Figures 7, 8), no assumptions should be made as for long-term scenarios. This is supported by the parallel results (to biodiversity) obtained in our model for extinction debt (Figure 7). While the biodiversity figure shows the variation of current (gross) biodiversity values, extinction debt shows the future extinction of species due to events in the past – which occurs because of time delays between impacts on species and the species' ultimate disappearance (Jackson and Sax, 2010). Thus, extinction debt provides key information about the equilibrium biodiversity in the Wet Tropics, which refers to the future (long-term) net biodiversity values once extinction debt reaches zero and the system comes into equilibrium(Jackson and Sax, 2010). The difference between the current (gross) biodiversity and the equilibrium (net) biodiversity is particularly important under the LSP scenario, where the short term positive-steady biodiversity results could become negative in the long-term due to the increasing extinction debt (see Figure 7). As a result, we argue that any short- and medium-term positive biodiversity values in the Wet Tropics need to be considered with caution, due to potential negative long-term conclusions. Furthermore, the creation of new protected areas in the Wet Tropics could be currently weakening protection forces elsewhere in Australia, especially in Queensland – where only 7.92% of land is currently protected (far below the 17% stated in the Aichi Biodiversity Target 11). This could be related to the so-called public biodiversity discourse impacts explored by Hill *et al.* (2015b). This concept says that society associates increases in protected areas with increasing pro-conservation community sentiments, thus leading to a public perception that more biodiversity is being protected (e.g. in the Wet Tropics), and thereby reducing public discourse about the risks of biodiversity loss elsewhere (e.g. in the rest of Queensland/Australia). Thus, rather than enhancing pro-conservation community sentiments in the rest of the country, creation of protected areas in the Wet Tropics could be diminishing them (Hill *et al*., 2015b).

Overall, we argue that the positive results obtained under our BAU scenario for the Wet Tropics cannot be compared to BAU scenarios in other tropical areas. This is because the Wet Tropics possesses its own particular socio-economic, environmental, cultural and political characteristics. Furthermore, BAU scenarios undergo periods of non-linear and abrupt changes, thus differing from place to place (Muller, 2014) and limiting the predictability and extrapolation of land-systems. Due to this, deciding which approach (LSP or LSH) is more sustainable for a tropical SES is difficult, considering the challenging goal of meeting different targets under single LSP and LSH scenarios (Law *et al*., 2015). In fact, the debate over LSP or LSH could be blurred by the differing spatial scales considered (Ekroos *et al*., 2016). Hence, some scholars suggest other approaches, such as a mixture of LSH with LSP (Gordon *et al*., 2016; Renwick and Schellhorn, 2016), or multiple-scale land sparing (Ekroos *et al*., 2016), as potential pathways to overcome the LSP versus LSH dichotomy (Renwick and Schellhorn, 2016).

5. Conclusions

The take home-message of this article is two-fold:

(1) The current BAU context in the forested SES of the Wet Tropics region is helping to reconcile biodiversity conservation, climate change mitigation and sugarcane production. This is due to the stronger conservation forces compared to economic ones; which could have its origin in the combination and integration of bottom-up and top-

down conservation forces over the last decades, as well as further socio-political, legal, environmental-scientific, economic, governance and geographical factors. This is an outstanding achievement for a tropical region; considering that most of them are characterized for having stronger economic, land clearing forces compared to conservation, thus enhancing biodiversity loss, habitat destruction, climate change, and other environmental issues.

(2) Deciding between LSP or LSH approaches cannot be an either-or proposition. Thus, a mixture of sharing and sparing will be in order to meet conservation goals in a world with a growing demand for different ES. Tropical SES are complex, dynamic and non-linear systems; therefore, the atypical BAU context in the Wet Tropics cannot be extrapolated nor compared to BAU scenarios from other tropical areas, as the Wet Tropics possesses its own particular socio-economic, environmental, cultural and political context. Thus, each geographic context, and set of stakeholders, will need to explore alternative sustainable solutions based on their own local and regional characteristics. Nonetheless, the LSP versus LSH framework has the potential to meet multiple goals that, when integrated within spatially explicit models, can be used to explore sustainable solutions for complex SES.

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